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Comparison of ERBS Orbit Determination Accuracy Using Batch Least-Squares and Sequential Methods*

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ABSTRACT

The Flight Dynamics Division (FDD) at the Goddard Space Flight Center (GSFC) commissioned Applied Technology Associates, Incorporated, to develop the Real-Time Orbit Determination/Enhanced (RTOD/E) system as a prototype system for sequential orbit determination of spacecraft on a DOS-based personal computer (PC). This paper presents an overview of RTOD/E capabilities and presents the results of a study to compare the orbit determination accuracy for a Tracking and Data Relay Satellite System (TDRSS) user spacecraft obtained using RTOD/E on a PC with the accuracy of an established batch least-squares system, the Goddard Trajectory Determination System (GTDS), operating on a mainframe computer.

RTOD/E was used to perform sequential orbit determination for the Earth Radiation Budget Satellite (ERBS), and the Goddard Trajectory Determination System (GTDS) was used to perform the batch least-squares orbit determination. The estimated ERBS ephemerides were obtained for the August 16–22, 1989, timeframe, during which intensive TDRSS tracking data for ERBS were available. Independent assessments were made to examine the consistencies (overlap comparisons for the batch case and covariances and the first measurement residuals for the sequential case) of results obtained by the batch and sequential methods. Comparisons were made between the forward filtered RTOD/E orbit solutions and definitive GTDS orbit solutions for ERBS; the solution differences were less than 40 meters after the filter had reached steady state.

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1. INTRODUCTION

This paper describes a prototype of a sequential orbit determination system and compares the orbit determination accuracy for a Tracking and Data Relay Satellite (TDRS) System (TDRSS) user spacecraft using this prototype system with that achieved using an established batch least-squares system.

The National Aeronautics and Space Administration (NASA) has completed a transition from tracking and communications support of low Earth-orbiting satellites with a ground-based station network, the Ground Spaceflight Tracking and Data Network (GSTDN), to the geosynchronous relay satellite network, the TDRSS. TDRSS currently consists of three operational geosynchronous spacecraft (TDRS-East, TDRS-West, and TDRS-Spare) and the White Sands Ground Terminal (WSGT) at White Sands, New Mexico. TDRS-East, TDRS-West, and TDRS-Spare are located at 41, 174, and 171 degrees west longitude, respectively. The ground network provided only about 15-percent visibility coverage, while TDRSS has the operational capability to provide 85-percent to 100-percent coverage.

The Bilateration Ranging Transponder System (BRTS) is used to provide range and Doppler measurements for each TDRS. The ground-based BRTS transponders are tracked as if they were TDRSS user spacecraft. Since the positions of the BRTS transponders are known, their ranging data can be used to precisely determine the trajectory of the TDRS spacecraft.

To meet stringent accuracy requirements for definitive and predicted ephemerides in a timely manner for future low Earth-orbiting missions, there is an ongoing effort at Goddard Space Flight Center (GSFC) to improve the orbit determination methods and the analysis of them in such areas as force modeling, geophysical modeling, observation corrections, estimation methods, propagation methods, and numerical methods. Assessment of the relative orbit determination accuracy of the sequential and batch least-squares estimation methods is the focus of this paper.

The orbit determination methods used in this study are the batch least-squares method used for current operational orbit determination support and a sequential method implemented in a prototype system used for analysis at the GSFC Flight Dynamics Facility (FDF). The batch weighted least-squares algorithm implemented in the Goddard Trajectory Determination System (GTDS) estimates the set of orbital elements, force modeling parameters, and measurement-related parameters that minimize the squared difference between observed and calculated values of selected tracking data over a solution arc. GTDS resides and operates on the mainframe computer system at the FDF. The sequential estimation algorithm implemented in a prototype system, the Real-Time Orbit Determination/Enhanced (RTOD/E), simultaneously estimates the TDRSS user and relay spacecraft orbital elements and other parameters in the force and observation models at each measurement time. RTOD/E performs forward filtering of tracking measurements using an extended Kalman filter with a process noise model to account for geopotential-induced errors, as well as Gauss-Markov processes for drag, solar radiation pressure, and measurement biases. The main features of RTOD/E are described in Section 2.

RTOD/E and GTDS are used in this study to perform orbit determination for the Earth Radiation Budget Satellite (ERBS) and the TDRSs. The estimated ERBS ephemerides were

obtained for the August 16–22, 1989, timeframe, during which intensive TDRSS tracking data for ERBS were available. This particular timeframe was chosen because detailed orbit determination analysis was previously performed using GTDS (Reference 1). Comparisons were made between the RTOD/E and GTDS results. Independent assessments were made to examine the consistencies (overlap comparisons for the batch case and state error covariances for the sequential case) of results obtained by the batch and sequential methods.

Section 3 of this paper describes the orbit determination and evaluation procedures used in this study, and Section 4 gives the results obtained by the batch least-squares and sequential estimation methods and provides the resulting consistency and cross comparisons. Section 5 presents the conclusions of this study.

2. DESCRIPTION OF RTOD/E

RTOD/E was recently developed by Applied Technology Associates, Incorporated (ATA) for the GSFC Flight Dynamics Division (FDD) to respond to the need for a real-time estimation capability, to address future increased TDRSS-navigation accuracy requirements, and to provide automation of some routine orbit determination operations. The goal for future orbit determination accuracy is 10 meters (1σ) total position error for the user and 25 meters (1σ) total position error for the TDRSs. RTOD/E provides a proof of concept for the use of sequential estimation techniques for orbit determination with TDRSS tracking data and offers the potential for enhanced accuracy navigation with real-time responsiveness. RTOD/E is a research tool for assessment of sequential estimation for FDF navigation applications in realistic operational situations.

RTOD/E uses an extended Kalman filter for sequential orbit estimation. With the sequential estimation method, each tracking measurement can be processed immediately upon receipt to produce an update of a spacecraft's state vector and auxiliary state parameters. This fact makes it well-suited for real-time or near-real-time operation. Sequential estimation is particularly well-suited to the development of systems to perform orbit determination autonomously on the spacecraft's onboard computer (Reference 2). Spacecraft orbit determination during and just after a maneuver is a critical support function for which orbit determination is needed in near-real-time. Therefore, sequential estimation is also well-suited for such an application. In addition, the forward filter can be augmented with a backward smoothing filter to further improve the overall accuracy, especially during periods without tracking data.

RTOD/E employs a sequential estimation algorithm with a process noise model to stochastically account for gravity model errors (References 3 and 4). In addition to the state vectors, the filter estimates free parameters of the force model and the measurement model, treating these parameters as random variables whose behavior is governed by a Gauss-Markov stochastic process. The primary capabilities of RTOD/E are the following:

- Simultaneously determine orbits for a TDRSS user and two TDRS spacecraft using TDRSS with/without BRTS tracking measurements.
- Separately determine the TDRS orbit using BRTS tracking measurements.

- Perform near-real-time orbit determination when supplied with near-real-time tracking data through NPI.
- Perform orbit determination using archived tracking data.
- Process TDRSS and BRTS range and two-way Doppler tracking measurements.
- Perform predictions for spacecraft orbits.
- Generate graphical displays of the spacecraft covariance estimates, measurement residuals, and ground-track while concurrently processing data.
- For each tracking configuration, estimate the spacecraft state vector, drag parameter, and solar reflectivity coefficient for the user spacecraft; the solar reflectivity coefficients for the TDRSs; and the range and range-rate bias. The estimated parameters are obtained sequentially after processing each measurement.

The NAS-to-PC Interface (NPI) is used for the near-real-time extraction and transfer of TDRSS and BRTS tracking data from a tracking data base on the NAS 8063 mainframe computer to the RTOD/E PCs (Reference 5).

3. ORBIT DETERMINATION AND EVALUATION PROCEDURE

This section describes the analysis procedures used in this study. The TDRSS and BRTS tracking data characteristics are presented in Section 3.1, and the orbit determination evaluation methodology and options used are described in Section 3.2.

3.1 TRACKING MEASUREMENTS

The user spacecraft chosen for this study was the Earth Radiation Budget Satellite (ERBS), which was deployed by the Space Transportation System (STS)-41G in October 1984. ERBS has a nearly circular orbit, with an altitude of approximately 600 kilometers, an inclination of 57 degrees, and a period of approximately 96 minutes. The time period chosen for this study was from 0 hours Greenwich mean time (GMT) on August 16, 1989, through 10 hours GMT on August 23, 1989. During this interval, an unusually dense TDRSS tracking of the ERBS satellite was made available. Another significant component of the tracking characteristics is that the tracking was scheduled by alternately using both relay spacecraft on a pass-by-pass basis. The tracking consisted of an average of 25 15-minute passes of two-way TDRSS range and Doppler observations each day. A timeline plot of the TDRSS tracking data distribution is given in Figure 1.

The typical scenario for BRTS tracking of the TDRSs during the period of study included approximately 4 minutes of range and two-way Doppler measurements from two ground transponders for each relay every 2 to 3 hours. BRTS stations for TDRS-East are located at White Sands and Ascension Island. BRTS stations for TDRS-West are located at White Sands, American Samoa, and Alice Springs, Australia. The Alice Springs station was inoperative during August 1989, the period of this study.

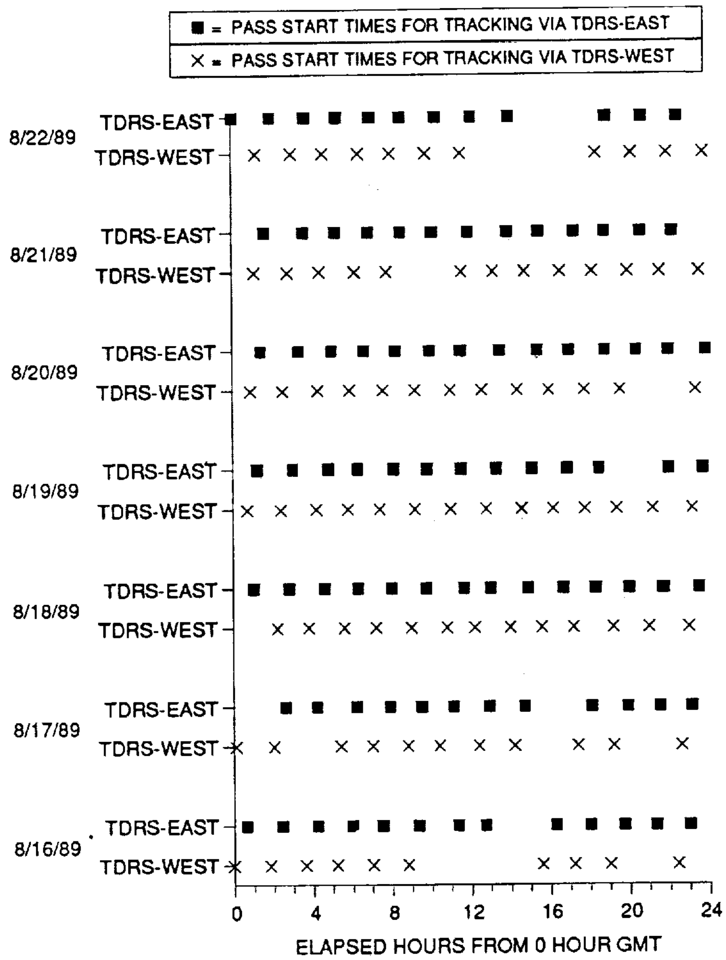

Figure 1. Tracking Data for ERBS

3.2 EVALUATION METHODOLOGY

The evaluation methodologies for the batch least-squares and sequential estimation methods are described below. Table 1 gives the parameters and options for the simultaneous solutions of the user and relay spacecraft. Table 2 gives the force and measurement model specifications. Since there are some known differences between the GTDS and RTOD/E force models and since the RTOD/E TDRSS and BRTS measurement models were implemented independently from GTDS, the two systems are not expected to provide identical results. Therefore, this study assumes that each system is used in its optimal configuration.

Batch Least-Squares Method

Except for the variations noted, the computational procedures and mathematical methods used in this study are those used for routine operational orbit determination at the GSFC FDF. The batch weighted least-squares algorithm implemented in GTDS (Reference 6) solves for the set of orbital elements and other parameters that minimizes the squared difference between observed and calculated values of selected tracking data over a solution arc.

Table 1. Parameters and Options for the Simultaneous Solutions of User and Relay Spacecraft

ORBIT DETERMINATION PARAMETER OR OPTION	GTDS VALUES		RTOD/E VALUES	
	USER (ERBS)	RELAY (TDRS-EAST & TDRS-WEST)	USER (ERBS)	RELAY (TDRS-EAST & TDRS-WEST)
ESTIMATED PARAMETERS	STATE, DRAG SCALING PARAMETER (ρ_1), RANGE AND DOPPLER MEASUREMENT BIASES FOR TRACKING VIA EACH TDRS	STATE, TRANSPONDER DELAYS FOR EACH BRTS TRANSPONDER	STATE, COEFFICIENT OF DRAG, RANGE AND DOPPLER MEASUREMENT BIASES FOR TRACKING VIA EACH TDRS	STATE, SOLAR REFLECTIVITY COEFFICIENT (C_R), RANGE AND DOPPLER MEASUREMENT BIASES FOR TRACKING VIA EACH TRANSPONDER
INTEGRATION TYPE	FIXED-STEP COWELL	FIXED-STEP COWELL	VARIATION OF PARAMETERS	VARIATION OF PARAMETERS
COORDINATE SYSTEM OF INTEGRATION	MEAN OF 1950.0	MEAN OF 1950.0	MEAN OF 1950.0	MEAN OF 1950.0
INTEGRATION STEP SIZE (SECONDS)	30.0	600.0	60.0	600.0
TRACKING DATA	TDRSS	BRTS	TDRSS	BRTS
DATA RATE	1 PER 10 SECONDS	1 PER 10 SECONDS	1 PER 60 SECONDS	1 PER 60 SECONDS
DC CONVERGENCE PARAMETER	0.005	0.005	N/A	N/A
EDITING CRITERION	3σ	3σ	3σ	3σ
MEASUREMENT σ's:				
RANGE	30.0 METERS	10.0 METERS	0.4 METER	0.25 METER
DOPPLER	0.25 HERTZ	0.003 HERTZ	0.004 HERTZ	0.002 HERTZ
GAUSS-MARKOV PARAMETERS:	N/A	N/A		
DRAG HALF-LIFE			720 MINUTES	N/A
DRAG SIGMA			0.5	N/A
C_R HALF-LIFE			N/A	11520 MINUTES
C_R SIGMA			N/A	0.2
RANGE BIAS HALF-LIFE			60 MINUTES	60 MINUTES
RANGE BIAS SIGMA			6 METERS	4.5 METERS
DOPPLER BIAS HALF-LIFE			60 MINUTES	60 MINUTES
DOPPLER BIAS SIGMA			0.034 HERTZ	0.02 HERTZ
SATELLITE DIAMETER	2.45 METERS	9.42 METERS	2.45 METERS	9.42 METERS
SATELLITE MASS	2116 KILOGRAMS	2068 KILOGRAMS	2116 KILOGRAMS	2068 KILOGRAMS

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N/A = NOT APPLICABLE

Table 2. Force and Measurement Model Specifications

ORBIT DETERMINATION PARAMETER OR OPTION	GTDS VALUES		RTOD/E VALUES	
	USER (ERBS)	RELAY (TDRS-EAST & TDRS-WEST)	USER (ERBS)	RELAY (TDRS-EAST & TDRS-WEST)
GEOPOTENTIAL MODEL	GEM-T2 (50 x 50)	GEM-T2 (8 x 8)	GEM-10B (30 x 30)	GEM-10B (8 x 8)
ATMOSPHERIC DENSITY MODEL	HARRIS-PRIESTER FOR SOLAR FLUX 225	N/A	JACCHIA-WALKER DAILY SOLAR FLUX VALUES (253, 256, 258, 243, 231, 220, 200)	N/A
SOLAR AND LUNAR EPHEMERIDES	JPL DE-118	JPL DE-118	ANALYTICAL	ANALYTICAL
SOLAR REFLECTIVITY COEFFICIENT (C_R)	1.2	SEE TEXT	1.2	ESTIMATED
COEFFICIENT OF DRAG (C_D)	ESTIMATED	N/A	ESTIMATED	N/A
IONOSPHERIC REFRACTION CORRECTION	BENT MODEL	BENT MODEL	NO	NO
GROUND-TO-SPACECRAFT	NO	YES		
SPACECRAFT-TO-SPACECRAFT	YES	N/A		
TROPOSPHERIC REFRACTION CORRECTION	YES	YES	YES	YES
ANTENNA MOUNT CORRECTION	NO	NO	NO	NO
POLAR MOTION CORRECTION	YES	YES	NO	NO
EARTH TIDES	YES	NO	NO	NO

GEM = GODDARD EARTH MODEL
JPL = JET PROPULSION LABORATORY
N/A = NOT APPLICABLE

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Parameters solved for, other than the spacecraft state at epoch, include free parameters of the force model and/or the observation model. The options used for the study described in this paper are summarized in columns 2 and 3 of Tables 1 and 2.

The solar reflectivity coefficients (C_R) for TDRS-East and TDRS-West were not estimated in the simultaneous solutions of ERBS, TDRS-East, and TDRS-West but were applied. The values of C_R applied in the present calculations were obtained from separate solutions of TDRS-East and TDRS-West from a previous study where C_R values were estimated (Series C and D of Reference 1).

To evaluate the orbit determination consistency achievable with a particular choice of options using least-squares estimation, a series of seven 34-hour definitive solutions was performed with 10-hour overlaps between neighboring arcs. The GTDS Ephemeris Comparison Program was used to determine the root-mean-square (RMS) position differences between the definitive ephemerides for neighboring solutions in the 10-hour overlap time period. These "overlap" comparisons measure the adjacent solution consistency, not the absolute accuracy.

Sequential Estimation Method

RTOD/E uses a forward-processing extended Kalman filter for sequential orbit estimation. The mathematical algorithms and computational procedures are described in References 3

and 4. The specific options used in RTOD/E for this study are listed in the last two columns of Tables 1 and 2.

A good indicator of the consistency of the sequential estimation results is the state error covariance function generated during the estimation process (Reference 7). In addition, the relationship of the first predicted measurement residual of each tracking pass to the associated predicted residual variance provides an indication of the physical integrity of the state error covariance of the filtered orbits. These parameters were monitored during the sequential estimation process.

4. RESULTS AND DISCUSSION

The results of this study for the ERBS and relay spacecraft are presented in this section, along with an analysis of the results. Greater emphasis is placed on the ERBS results, since the primary objective is to study TDRSS user orbit determination. The orbit determination results using batch least-squares calculations and sequential estimation are given in Sections 4.1 and 4.2, respectively; the comparisons are presented in Section 4.3.

4.1 BATCH LEAST-SQUARES RESULTS

An extensive analysis of the batch least-squares orbit determination of ERBS and the TDRSs in terms of variations in the force models, measurement models, and solution modes was reported in Reference 1. The results reported here do not significantly differ from those of Reference 1. The only difference between the calculations of series M in Reference 1 and the present calculations is that in the present calculations the biases on TDRSS range and two-way Doppler measurements and the transponder delays for BRTS measurements were also estimated. (The options used for calculations of series M of Reference 1 are the same as those given in columns 2 and 3 of Tables 1 and 2, with the exception of the parameter set.) The choice to expand the state space of the least-squares solutions was motivated by the fact that the RTOD/E orbit determination algorithm estimates an equivalent set of bias parameters. The resulting differences are discussed below.

The RMS values of six ERBS overlap comparisons are summarized in Figure 2. The overlap values vary from about 4 to 17 meters. The mean and sample standard deviation of this distribution, in the form of *mean ± standard deviation*, is 13.3 ± 5.9 meters. The maximum total position differences over the same distribution vary between 6 and 46 meters, with mean and standard deviation of 29.7 ± 14.8 meters. The maximum position difference values for ERBS are typically a factor of 2 larger than the RMS values.

The RMS values of six TDRS-East and TDRS-West overlap comparisons are summarized in Figure 3. The overlap values for TDRS-East vary from about 14 to 45 meters. The mean and sample standard deviation of this distribution is 25.0 ± 10.7 meters. The maximum total position differences over the same distribution vary between 17 and 58 meters, with mean and standard deviation of 33.9 ± 13.5 meters. The overlap values for TDRS-West vary from about 19 to 42 meters. The mean and the sample standard deviation of this distribution is 25.2 ± 9.0 meters. The maximum total position differences over the same distribution vary between 25 and 63 meters, with mean and standard deviation of 35.4 ± 14.2 meters. The

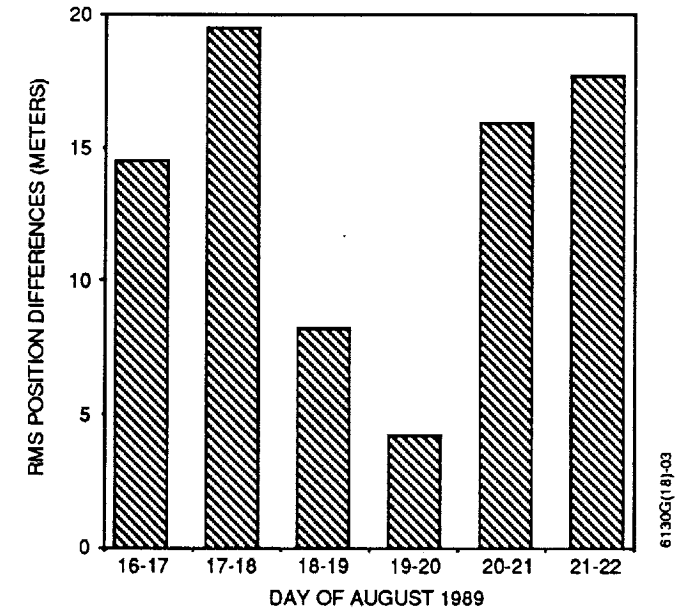

Figure 2. ERBS Overlap Comparisons

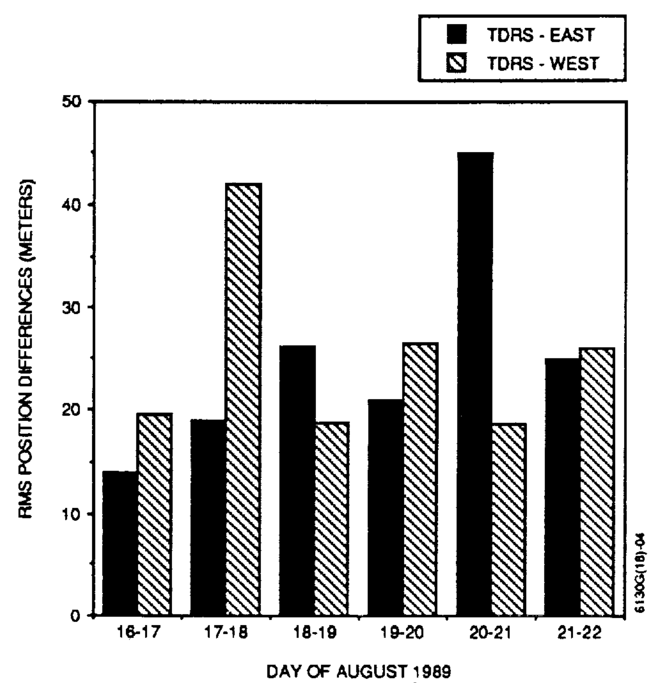

Figure 3. TDRS-East and TDRS-West Overlap Comparisons

maximum position difference values for the TDRSs are typically a factor of 1.2 larger than the RMS values.

The possible advantage of estimating a set of bias parameters (as was done in this study) versus not estimating the set (as was done in the series M calculation of Reference 1) was evaluated. The mean values of the range and Doppler measurement residuals (i.e., the observed-minus-computed values for each solution) as calculated in Reference 1 indicated the existence of a systematic error. The mean range measurement residuals varied between 6.3 ± 4.7 meters and 7.6 ± 4.6 meters for the seven solution arcs. The mean Doppler measurement residuals varied between −12.7 ± 91.1 millihertz and −17.5 ± 83.6 millihertz. The estimation of a set of bias parameters in the calculations in this study effectively removed the systematic error, thereby significantly reducing the mean range and mean Doppler measurement values, as expected. The standard deviations of the residuals were also somewhat reduced. However, although the removal of a bias may improve accuracy, it was not expected to improve consistency. As a matter of fact, the mean RMS overlap value without estimating for a set of bias parameters (series M of Reference 1) was comparable for ERBS (13.1 ± 6.1 meters) and somewhat smaller for TDRS-East (21.6 ± 7.9 meters) and TDRS-West (18.0 ± 9.2 meters).

4.2 SEQUENTIAL ESTIMATION RESULTS

During sequential processing of the TDRSS and BRTS measurements using RTOD/E, the state error covariance function (2σ) was closely monitored. The filter was started with high initial diagonal values in the covariance matrix. In the initial phases of filtering, the covariance values for ERBS were as high as 1200 meters and those for the TDRSs were 800 meters. However, this is not unusual before the filter has reached steady-state performance. After an initial filter settling period (about 24 hours), the covariance values varied from about 15 to 30 meters in the RMS position for ERBS and 40 to 60 meters for the TDRSs. The covariance values dropped to their lowest levels during a tracking pass and then gradually rose to the maximum values during the time update phase (propagation phase).

The first predicted range residuals of ERBS tracking passes after the filter processed the tracking data for 5 days are shown in Figure 4. The tracking passes via TDRS-East and TDRS-West are plotted separately. The value of the residual varied from nearly −5 meters to about 8 meters for passes via TDRS-East and from −8 meters to about 20 meters for passes via TDRS-West. The largest value (19.4 meters) occurred after about 1 hour of the prediction period following the previous tracking pass. The larger scatter for passes via TDRS-West is most likely attributable to the absence of BRTS tracking of TDRS-West by the Alice Springs station. The postmeasurement-update range residuals were negligibly small, typically of the order of 0.3 meter or less.

The estimated force model parameters varied as a function of time and were updated after each measurement processed. The time variation of the atmospheric drag coefficient for ERBS is shown in Figure 5. It varied from a low value of 1.6 to a high value of 3.0. The time variations of the solar radiation pressure coefficient for TDRS-East and TDRS-West are given in Figures 6 and 7, respectively. After the filter has reached steady state, the coefficient varied between 1.4 and 1.55.

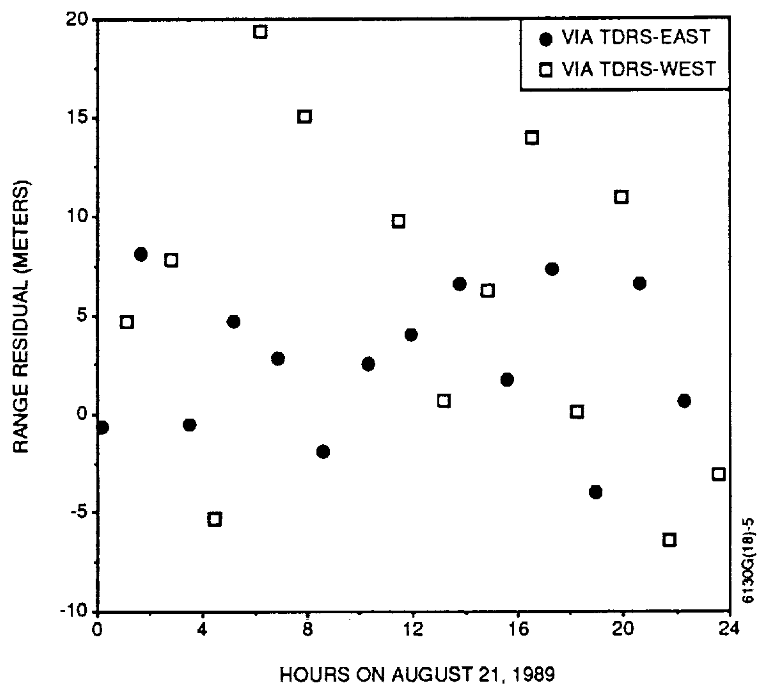

Figure 4. First Predicted Range Residual of TDRSS Tracking Passes for ERBS

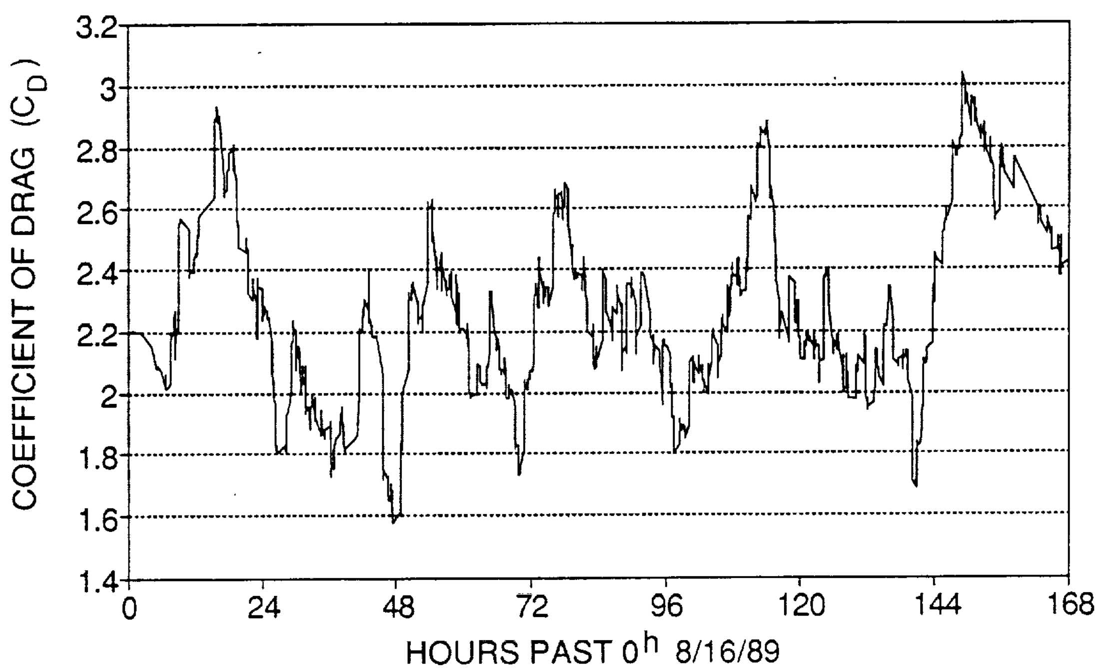

Figure 5. Coefficient of Atmospheric Drag (C_D) for ERBS

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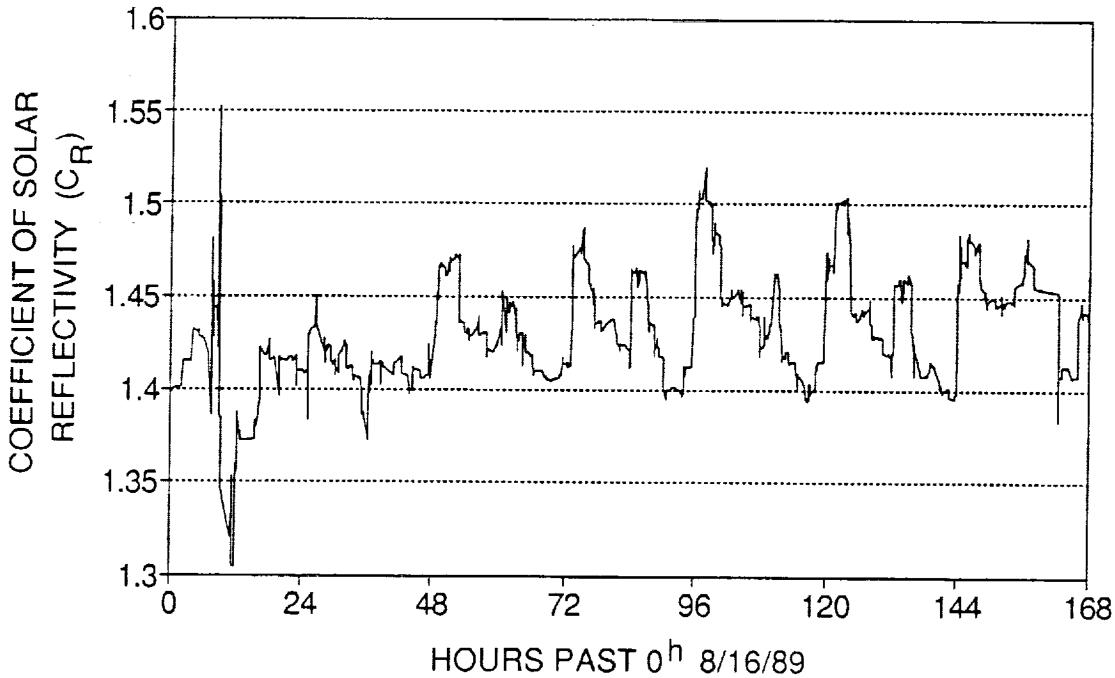

Figure 6. **Coefficient of Solar Radiation Pressure (C_R) for TDRS-East**

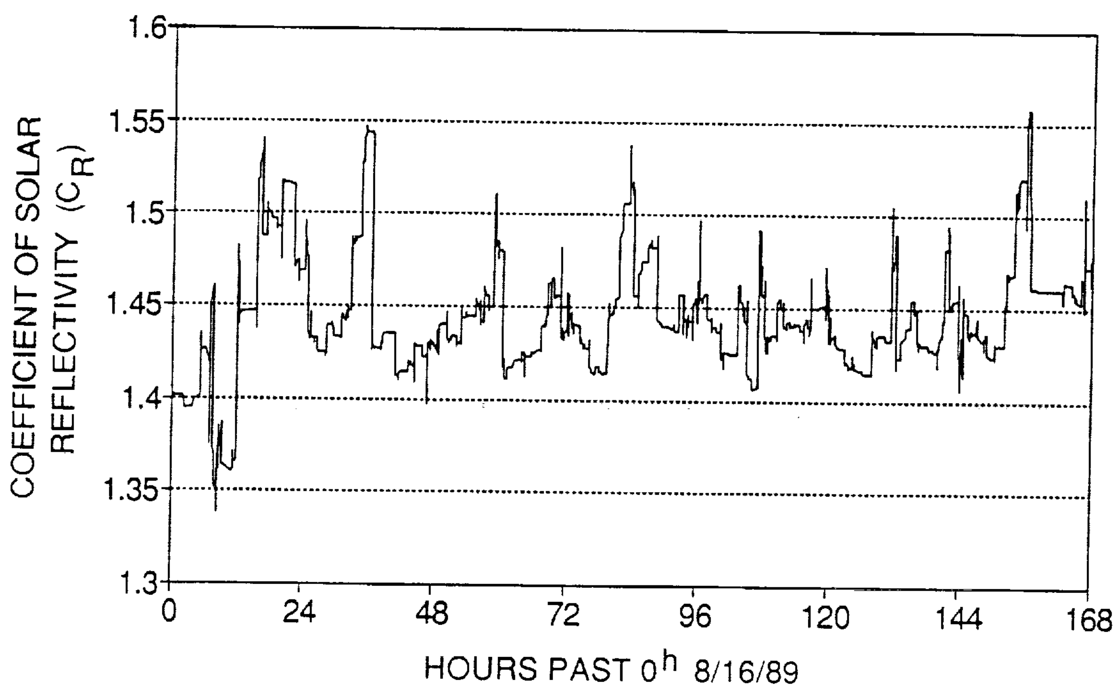

Figure 7. **Coefficient of Solar Radiation Pressure (C_R) for TDRS-West**

The solar flux values are input to RTOD/E on a daily basis. The time variation of the flux value over the 24-hour period is not input. Therefore, the atmospheric drag coefficient has to adjust itself for the variation (Figure 5). RTOD/E models the area of the TDRS to be a constant throughout the day, whereas in actuality the TDRS area exposed to the solar flux varies with a 24-hour period. The C_R estimated values for TDRS-East, shown in Figure 6, display an approximately repeated variation over 24-hours for the last 5 days during steady-state performance. Such a clear signature of variation is not evident in the C_R values for TDRS-West shown in Figure 7.

The time variation of the estimated range bias values for ERBS via TDRS-East and TDRS-West are shown in Figures 8 and 9, respectively. The bias values varied from approximately –3 meters to approximately 20 meters, with an average value of approximately 4 meters. There are some known physical phenomena and considerations that are absorbed in the estimation of the range bias. The variation in the offset of the ERBS antenna position from the center of mass is not modeled in RTOD/E. The time-varying tropospheric refraction delay and ionospheric refraction delay, which are not modeled in the measurement model, are absorbed in the range bias estimates.

4.3 COMPARISON OF BATCH AND SEQUENTIAL ESTIMATION RESULTS

Comparisons of the estimated ERBS orbits between GTDS solutions and RTOD/E forward-filtered solutions are presented in Figures 10 and 11. Figure 10 shows the differences during the first day of the filtered solution. Since the filter had not reached steady state during the early phases of this period, the position difference was as large as about 600 meters. However, this difference is not larger than the corresponding state error covariance values of the filter, an indicator of the internal consistency of the filtered solution. After the filter had reached steady state, the differences between the GTDS and RTOD/E solutions were much smaller than on the first day. Therefore, these results were plotted in Figure 11 with a different vertical scale; the position differences shown in this figure are all less than 40 meters. The maximum difference did not increase or decrease toward the end of the 7-day comparison period. The maximum difference of less than 40 meters is consistent within the cumulative consistencies of batch and sequential solutions.

A significant part of the difference between the batch and sequential orbit determination results in Figure 11 can be attributed to the differences in the force and measurement models used for GTDS and RTOD/E. Quantitative estimates for some of these model difference effects are available from previous studies using GTDS. It was reported in Reference 1 that the maximum position difference for definitive ERBS orbits using the GEM-T2 (50 x 50) and GEM-10B (36 x 36) geopotential models can be as high as 30.1 ± 5.2 meters. RTOD/E uses the GEM-10B geopotential model with order and degree 30. Due to the inclusion of a process noise model for geopotential errors in RTOD/E and its absence in GTDS, the impact differences in the models used would be different in the two systems. Estimates of the effects of differences in the Harris-Priester and Jacchia-Walker atmospheric density models are not available but may be significant. The maximum position differences in the definitive ERBS orbits due to the presence and absence of ionospheric refraction correction in the measurement model for the spacecraft-to-spacecraft leg can be 2.6 ± 0.9 meters (Reference 1). The maximum position difference due to polar motion and solid Earth tide effects are about

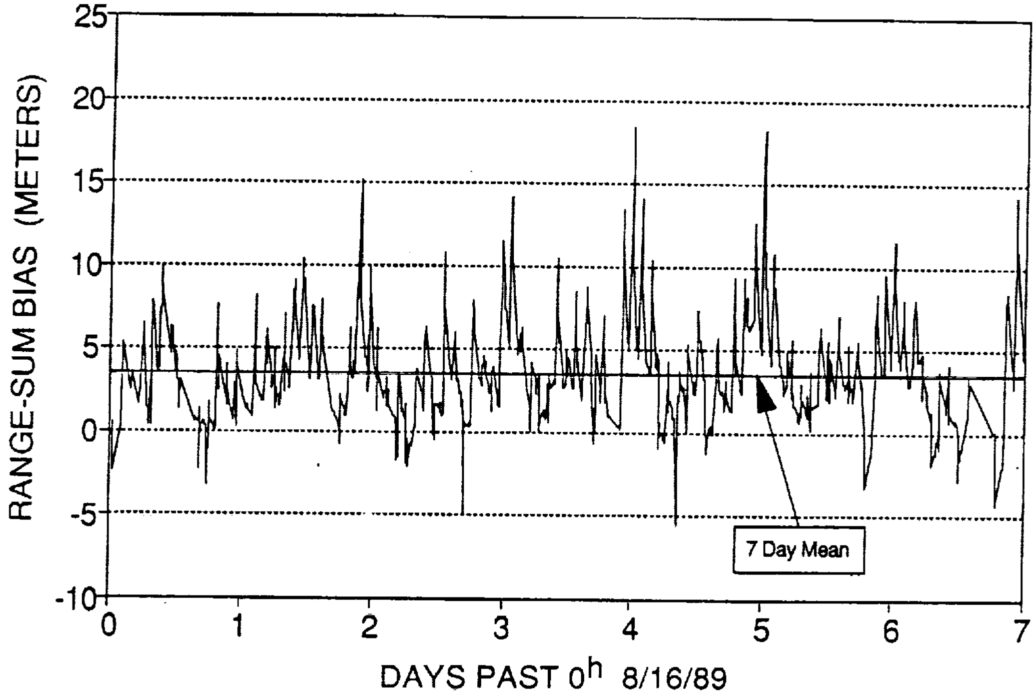

Figure 8. ERBS Range Bias via TDRS-East

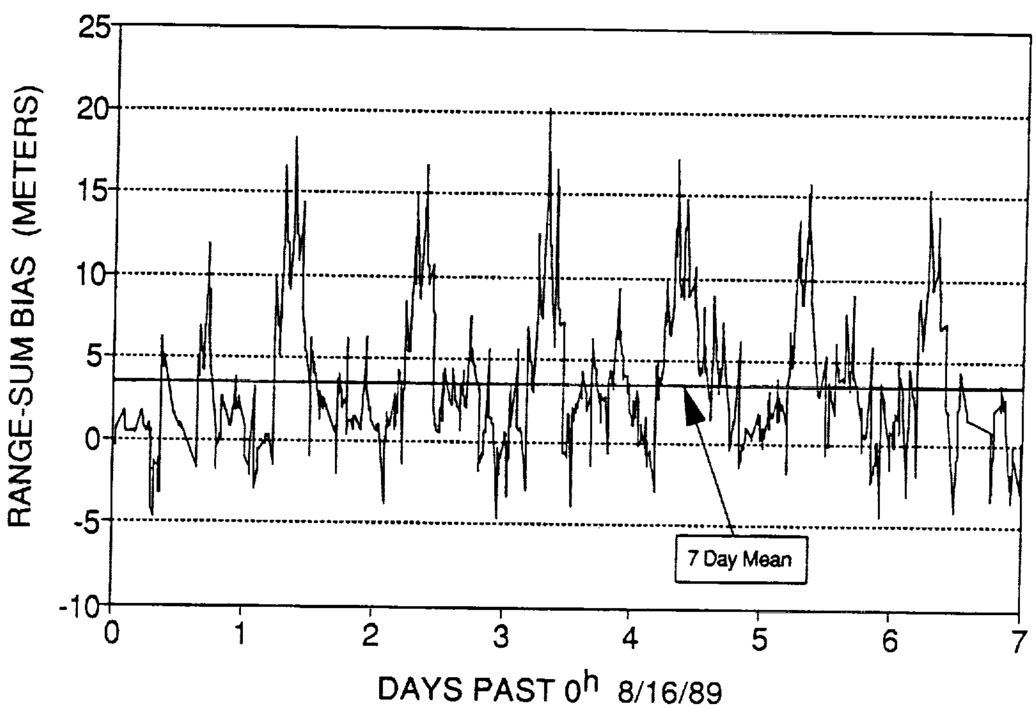

Figure 9. ERBS Range Bias via TDRS-West

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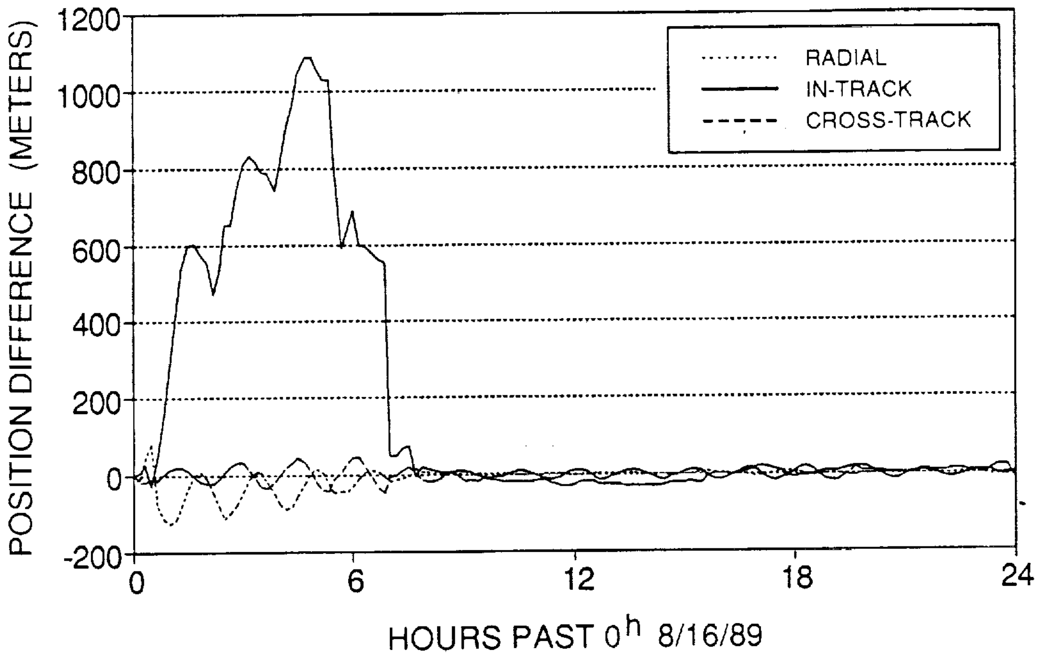

Figure 10. Comparison of Estimated GTDS and RTOD/E Ephemerides for ERBS (Radial, In-Track, and Cross-Track Components)

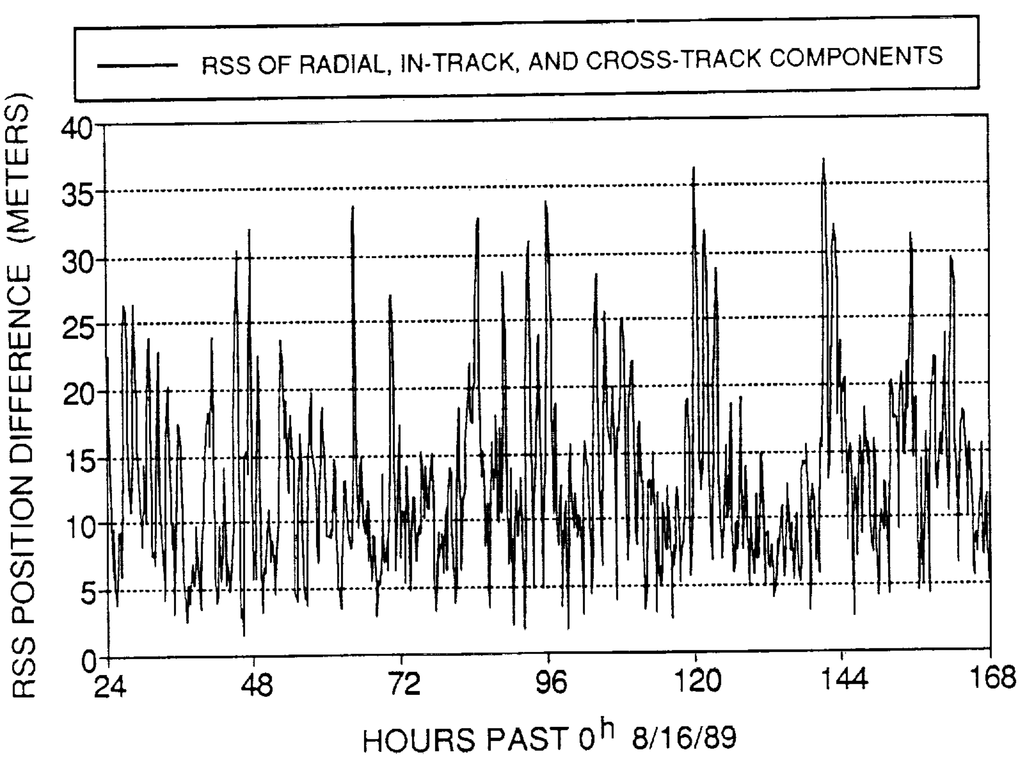

Figure 11. Comparison of Estimated GTDS and RTOD/E Ephemerides for ERBS (RSS of Components)

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8.3 ± 1.0 meters and 7.0 ± 3.2 meters, respectively. A more detailed analysis of the influence of polar motion and solid Earth tides on ERBS orbits is given in Reference 8.

Another source of the difference between the GTDS and RTOD/E estimated ephemerides is due to the fundamental difference in the way the estimated parameters are obtained in the batch least-squares and sequential estimation techniques. In the batch least-squares method, a single set of parameter values is estimated over an entire arc. In the sequential estimation process, the set of estimated parameter values is updated at each measurement time. The time variations in selected estimated parameters were shown in Figures 5 through 9.

Based on the magnitude of these differences and the differences in the estimation techniques, the maximum position difference of about 40 meters between the GTDS and RTOD/E results is not large.

5. REMARKS

The results presented in this paper were obtained using dense-tracking TDRSS measurements for ERBS. A previous study of ERBS with single-relay (TDRS-East only) TDRSS tracking has shown that to achieve the highest precision orbit determination using the batch least-square method, the tracking coverage should not fall below 10 minutes every two orbits (Reference 9). The tracking coverage used in the present study, as shown in Figure 2, was well above this criterion. The impact of tracking coverage on accuracy using sequential estimation techniques will be pursued in future studies. In theory, the filter is expected to be more sensitive to large gaps in tracking data than the batch least-squares method; but, on the other hand, it would benefit more from more continuous tracking than would the batch least-squares method.

An investigation to assess the prediction accuracy measured by comparing propagated solutions with the definitive solutions using GTDS and RTOD/E is in progress.

6. CONCLUSIONS

This study presented an analysis of TDRSS user orbit determination using a batch least-squares method and a sequential estimation method. Independent assessments were performed of the orbit determination consistency within each method, and the estimated orbits obtained by the two methods were also compared. This assessment is applicable to the dense-tracking measurement scenario for tracking ERBS.

In batch least-squares method analysis, the orbit determination consistency for ERBS, which was heavily tracked by TDRSS during August 1989, was found to be about 15 meters in the RMS overlap comparisons and about 30 meters in the maximum position differences in overlap comparisons. In sequential method analysis, the consistency was found to be about 15 to 30 meters in the 2σ state error covariance function.

After the filter had reached steady state, the differences between the definitive batch least-squares ephemerides and the forward filtered sequentially estimated ephemerides were

no larger than 40 meters, which is approximately the limit of the consistency for each separate method. Since the two methods of determining orbits are algorithmically and computationally independent, an accuracy level of about 40 meters (3σ) may be assigned to the orbits determined by either method from the present analysis, barring any tracking-system-related systematic error. Further studies will investigate the relative qualities of the two methods within this difference.

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